MICHAEL S. GAZZANIGA

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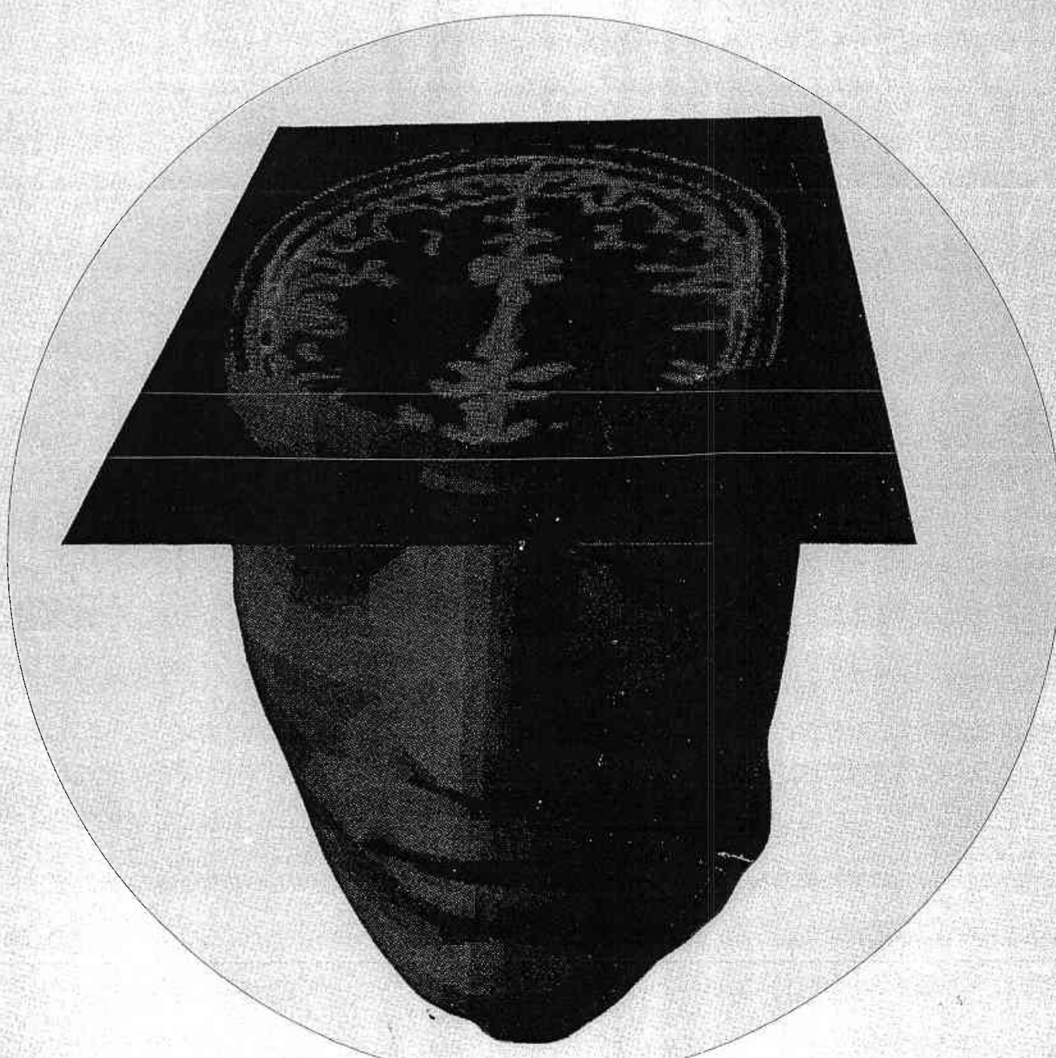
THE COGNITIVE NEUROSCIENCES



THE COGNITIVE NEUROSCIENCES

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11 Physical Reasoning in Infancy

RENÉE BAILLARGEON

ABSTRACT How do infants learn about the physical world? Current research on the development of infants' reasoning about various types of physical phenomena (e.g., support and collision phenomena) points to two developmental patterns that recur across ages and phenomena. The first pattern is that, when learning about a new physical phenomenon, infants first form a preliminary, all-or-none concept that captures the essence of the phenomenon but few of its details. With further experience, this initial concept is progressively elaborated. Infants slowly identify discrete and continuous variables that are relevant to the initial concept, study their effects, and incorporate this accrued knowledge into their reasoning, resulting in increasingly accurate predictions over time. The second developmental pattern is that, after identifying a continuous variable as being relevant to an initial concept, infants succeed in reasoning about the variable qualitatively before they are able to do so quantitatively. This chapter reviews some of the evidence for these two developmental patterns. It is argued that the patterns reflect, at least indirectly, the nature and properties of the mechanisms infants bring to the task of learning about the physical world.

A long-standing concern of infancy research has been the description of infants' knowledge about the physical world. Traditionally, this research tended to focus on infants' understanding of occlusion events. When adults see an object occlude another object, they typically assume that the occluded object continues to exist behind the occluder. Piaget (1952, 1954) was the first to examine whether infants hold the same assumption. He concluded that it is not until infants are approximately 9 months old that they begin to appreciate that objects continue to exist when masked by other objects. This conclusion was based mainly on analyses of infants' performance in manual search tasks. Piaget noted that, prior to 9 months or so of age, infants do not search for objects they have observed being hidden. If an attractive toy is covered with a cloth, for example, young infants make no attempt to lift the cloth and grasp the toy, even though they are capable (beginning at approximately 4 months) of performing each of these actions. Piaget took this finding to suggest that young infants do not yet understand occlusion events and incorrectly assume that objects cease to exist when concealed by other objects.

In subsequent years, numerous reports were published confirming Piaget's (1952, 1954) observation that young infants typically fail to search for hidden objects (for reviews of this early research, see Gratch, 1976; Schuberth, 1983; and Harris, 1987). Piaget's *interpretation* of his observation, however, eventually came into question. Researchers came to realize that young infants might perform poorly in search tasks not because of incorrect beliefs about occlusion events but because of difficulties associated with the planning of means-end search sequences (e.g., Bower, 1974; Baillargeon, Spelke, and Wasserman, 1985; Baillargeon et al., 1990; Diamond, 1991). This led investigators to seek alternative methods for exploring infants' beliefs about occluded objects, methods that did not require infants to perform means-end action sequences.

A well-established finding in infancy research, infants' tendency to look longer at novel than at familiar stimuli (for reviews, see Banks, 1983; Olson and Sherman, 1983; Fagan, 1984; Bornstein, 1985; and Spelke, 1985), suggested an alternative method for investigating infants' intuitions about occlusion events. In a typical experiment, infants are presented with two test events: a possible and an impossible event. The possible event is consistent with the belief that objects continue to exist when occluded; the impossible event, in contrast, violates this belief. The rationale is that if infants possess such a belief, they will perceive the impossible event as more novel or surprising than the possible event and will therefore reliably look longer at the impossible than at the possible event.

Using this violation-of-expectation method, investigators have demonstrated that, contrary to traditional claims, even very young infants appreciate that objects continue to exist when occluded (see Harris, 1989;

RENÉE BAILLARGEON Department of Psychology, University of Illinois, Champaign, Ill.

Spelke et al., 1992; and Baillargeon, 1993, for recent reviews). Next, two experiments, conducted with infants aged $3\frac{1}{2}$ and $2\frac{1}{2}$ months, are described that illustrate this conclusion.

In the first experiment (Baillargeon and DeVos, 1991), $3\frac{1}{2}$-month-old infants were habituated to a toy carrot standing on end that slid back and forth along a horizontal track whose center was occluded by a screen; the carrot disappeared at one edge of the screen and reappeared, after an appropriate interval, at the other edge (figure 11.1). On alternate trials, the infants saw a short or a tall carrot slide along the track. Following habituation, the midsection of the screen's upper half was removed, creating a large window. The infants then saw a possible and an impossible test event. In the possible event, the short carrot moved back and forth along the track; this carrot was shorter than the window's lower edge and so did not appear in the window when passing behind the screen. In the impossible event, the tall carrot moved along the track; this carrot was taller than the window's lower edge and hence should have appeared in the window but did not in fact do so. The infants tended to look equally at the short- and the tall-carrot habituation events but looked reliably longer at the impossible than at the possible test event. These results indicated that the infants (1) believed that each carrot continued to exist behind the screen; (2) appreciated that each carrot could not disappear at one end of the screen and reappear at the other end without having traveled the distance behind the screen; (3) were aware that the height of each carrot determined whether it would appear in the screen window; and hence (4) were surprised by the impossible event in which the tall carrot failed to appear in the window.

The results of this experiment provided evidence that, by $3\frac{1}{2}$ months of age, infants believe that objects continue to exist when occluded. The next experiment examined whether $2\frac{1}{2}$-month-old infants possess the same belief (Spelke et al., 1992). The infants were habituated to an event in which a ball rolled from left to right along a platform and disappeared behind a screen (figure 11.2). Next, the screen was removed to reveal the ball resting against a barrier at the end of

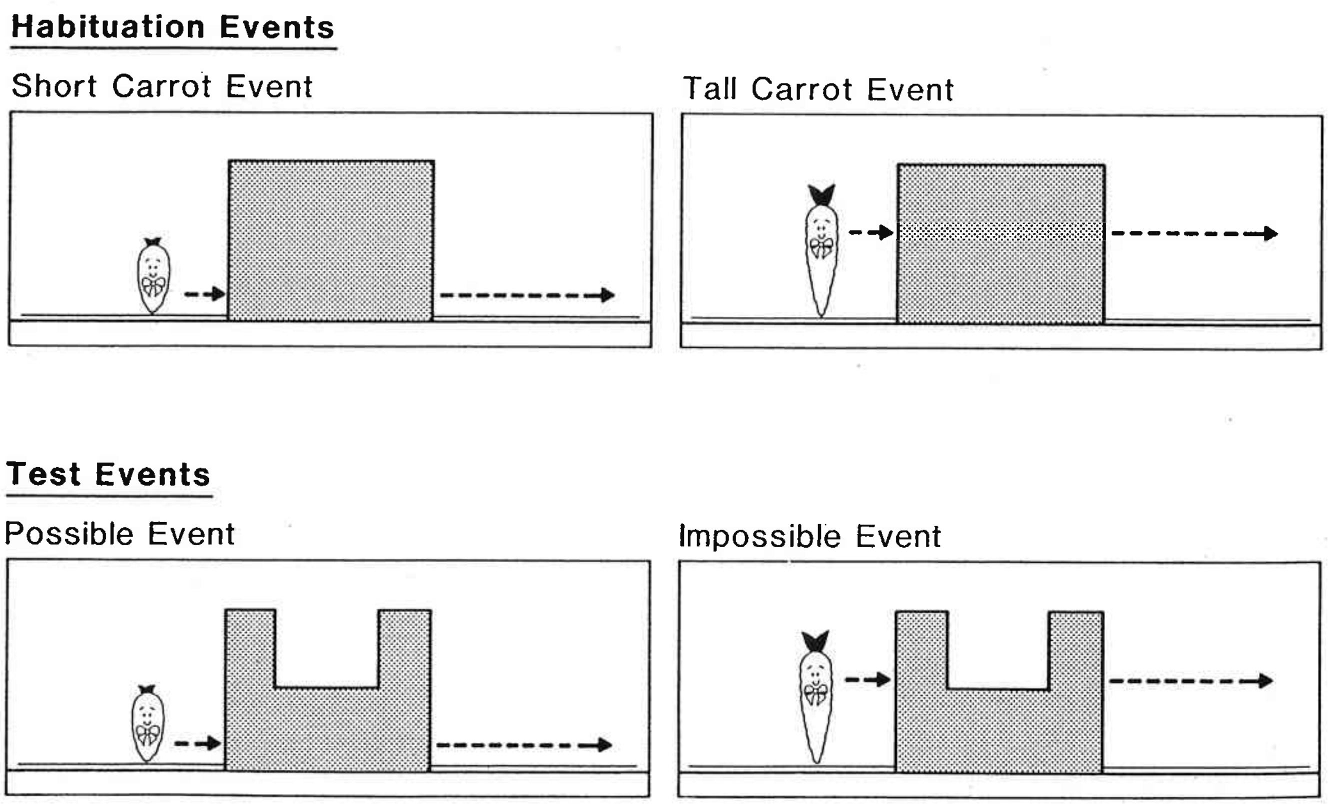

FIGURE 11.1 Test events used in Baillargeon and DeVos (1991).

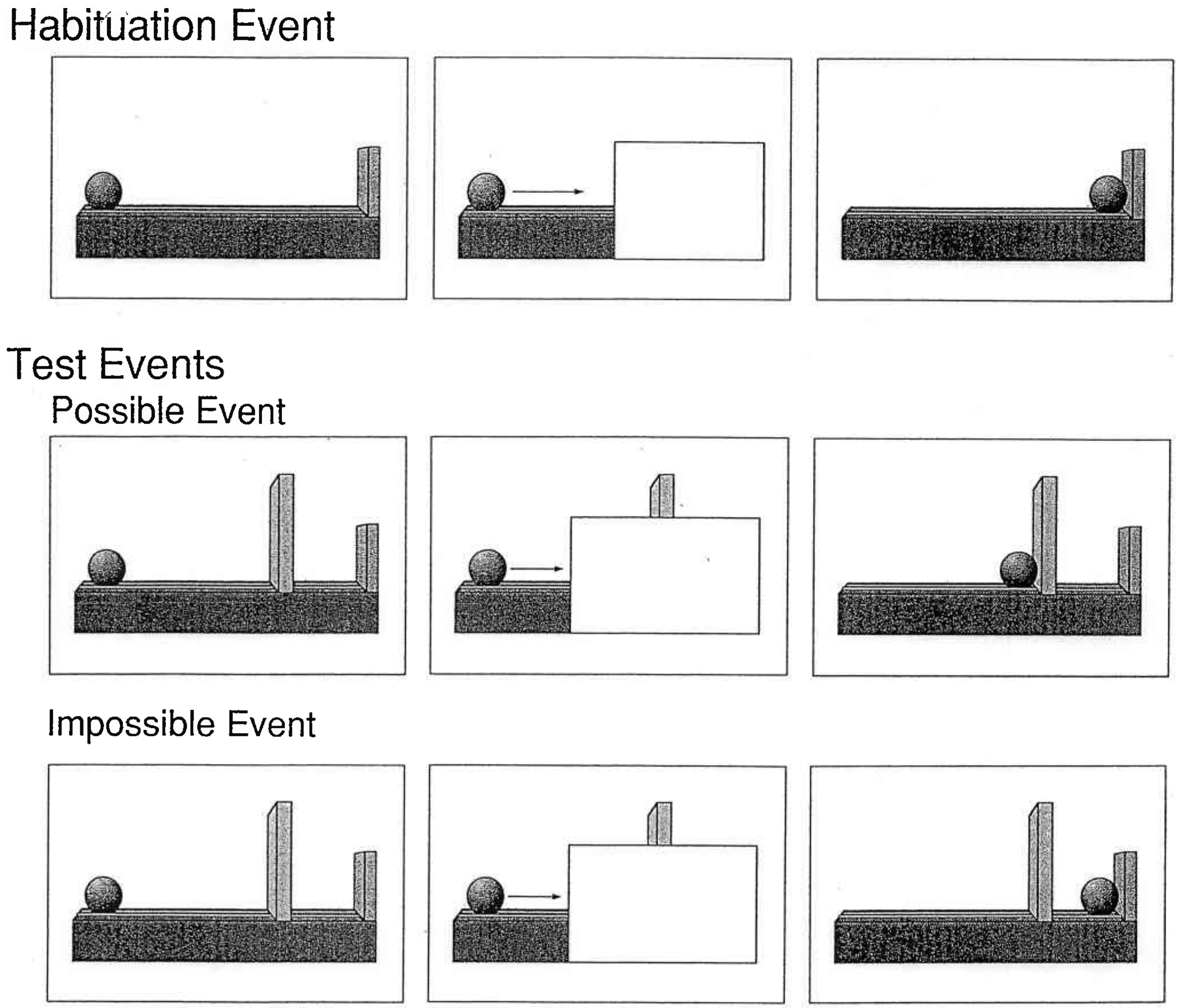

FIGURE 11.2 Test events used in Spelke and colleagues (1992). Schematic drawing based on the authors' description.

the platform. Following habituation, the infants saw two test events that were similar to the habituation event except that a tall, thin box stood behind and protruded above the screen. At the end of the possible event, the screen was removed to reveal the ball resting against the box. At the end of the impossible event, the screen was removed to reveal the ball resting against the barrier, as in the habituation event. The infants looked reliably longer at the impossible than at the possible event, suggesting that they (1) believed that the ball continued to exist behind the screen; (2) understood that the ball could not roll through the space occupied by the box; and hence (3) were surprised by the impossible event in which the ball was revealed on the far side of the box. This interpretation was supported by the results of a control condition in which the ball was lowered to the same final positions as in the possible and the impossible events.

The results of the two experiments just described indicated that, contrary to what had traditionally been claimed, even very young infants believe that objects continue to exist when masked by other objects. By virtue of their designs, the experiments also provided evidence that $2\frac{1}{2}$- to $3\frac{1}{2}$-month-old infants share adults' beliefs that objects cannot appear at two successive points in space without having traveled the distance between them and that objects cannot move through the space occupied by other objects.

How can we explain the presence of such sophisticated physical knowledge at such an early age? Over the past few years, my colleagues and I have begun to build a model of the development of infants' physical reasoning. The model is based on the assumption that infants are born not with substantive beliefs about objects, as researchers such as Spelke (1991; Spelke, Phillips, and Woodward, in press) and Leslie (1988, in press) have proposed, but with highly constrained mechanisms that guide the development of infants' reasoning about objects. The model is derived from findings concerning infants' intuitions about different physical phenomena (e.g., support, collision, and unveiling phenomena). Comparison of these findings points to two developmental patterns that recur across ages and phenomena. We assume that these patterns reflect, at least indirectly, the nature and properties of infants' learning mechanisms. These patterns are described along with some of the evidence supporting them (for further discussion of the model, see Baillargeon, in press, a, b, and Baillargeon, Kotovsky, and Needham, in press).

First pattern: Identification of initial concept and variables

The first developmental pattern is that, when learning about a new physical phenomenon, infants first form a preliminary, all-or-none concept that captures the essence of the phenomenon but few of its details. With further experience, this *initial concept* is progressively elaborated. Infants slowly identify discrete and continuous *variables* that are relevant to the initial concept, study their effects, and incorporate this accrued knowledge into their reasoning, resulting in increasingly accurate predictions over time.

To illustrate the distinction between initial concepts and variables, I will summarize experiments on the development of young infants' knowledge about support phenomena (conducted with Amy Needham, Julie DeVos, and Helen Raschke), collision phenomena (conducted with Laura Kotovsky), and unveiling phenomena (conducted with Julie DeVos).

Knowledge about Support Phenomena Our research on young infants' ability to reason about support phenomena has focused on simple problems involving a box and a platform. Our first experiment asked whether $4\frac{1}{2}$-month-old infants understand that a box can be stable when released *on* but not *off* a platform (Needham and Baillargeon, 1993). The infants again saw a possible and an impossible test event (figure 11.3). In the possible event, a gloved hand deposited a box on a platform and then withdrew a short distance, leaving the box supported by the platform. In the impossible event, the hand deposited the box beyond the platform and then again withdrew, leaving the box suspended in midair with no apparent means

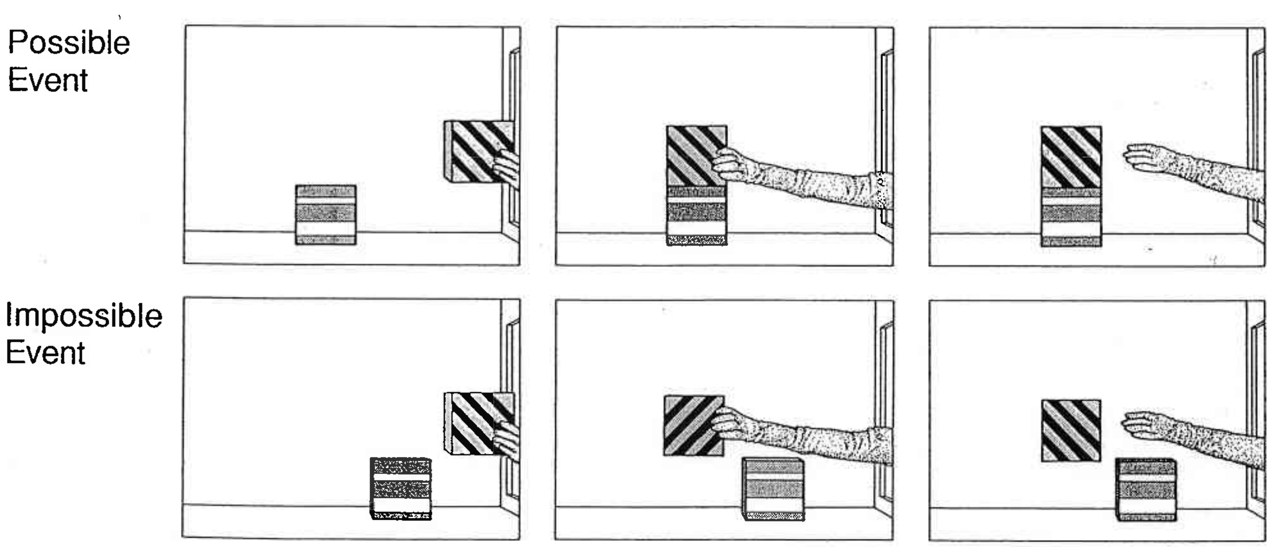

Figure 11.3 Test events used in Needham and Baillargeon (1993).

of support. Additional groups of $4\frac{1}{2}$-month-old infants were tested in two control conditions. In one, the infants saw the same test events as the infants in the experimental condition except that the hand never released the box, which was therefore continually supported. In the other control condition, the infants again saw the same test events as the infants in the experimental condition except that the box fell to the floor of the apparatus when released by the hand beyond the platform.

The infants in the experimental condition looked reliably longer at the impossible than at the possible event, whereas the infants in the two control conditions tended to look equally at the test events they were shown. Together, these results indicated that the infants in the experimental condition realized that the box could not remain stable without support and hence expected the box to fall in the impossible event and were surprised that it did not.

The results of this first experiment suggested that, by $4\frac{1}{2}$ months of age, infants expect a box to be stable if released on but not off a platform. Additional experiments conducted with different procedures yielded similar results with infants aged $5\frac{1}{2}$ months (Leslie, 1984; Kolstad and Baillargeon, 1994) and 3 months (Needham and Baillargeon, 1994).[1] Our next experiment (Baillargeon, Raschke, and Needham, 1994) asked whether $4\frac{1}{2}$-month-old infants not only understand that the box must be *in contact* with the platform in order to be stable but also appreciate what *type* of contact is needed for the box to be stable (figure 11.4). In the possible event, a gloved hand placed a small square box against the side of a large, open platform, on top of a smaller, closed platform. The impossible event was identical to the possible event except that the closed platform was much shorter so that the box now lay well above it.

The results indicated that the female infants looked reliably longer at the impossible than at the possible event, suggesting that they realized the box was inade-

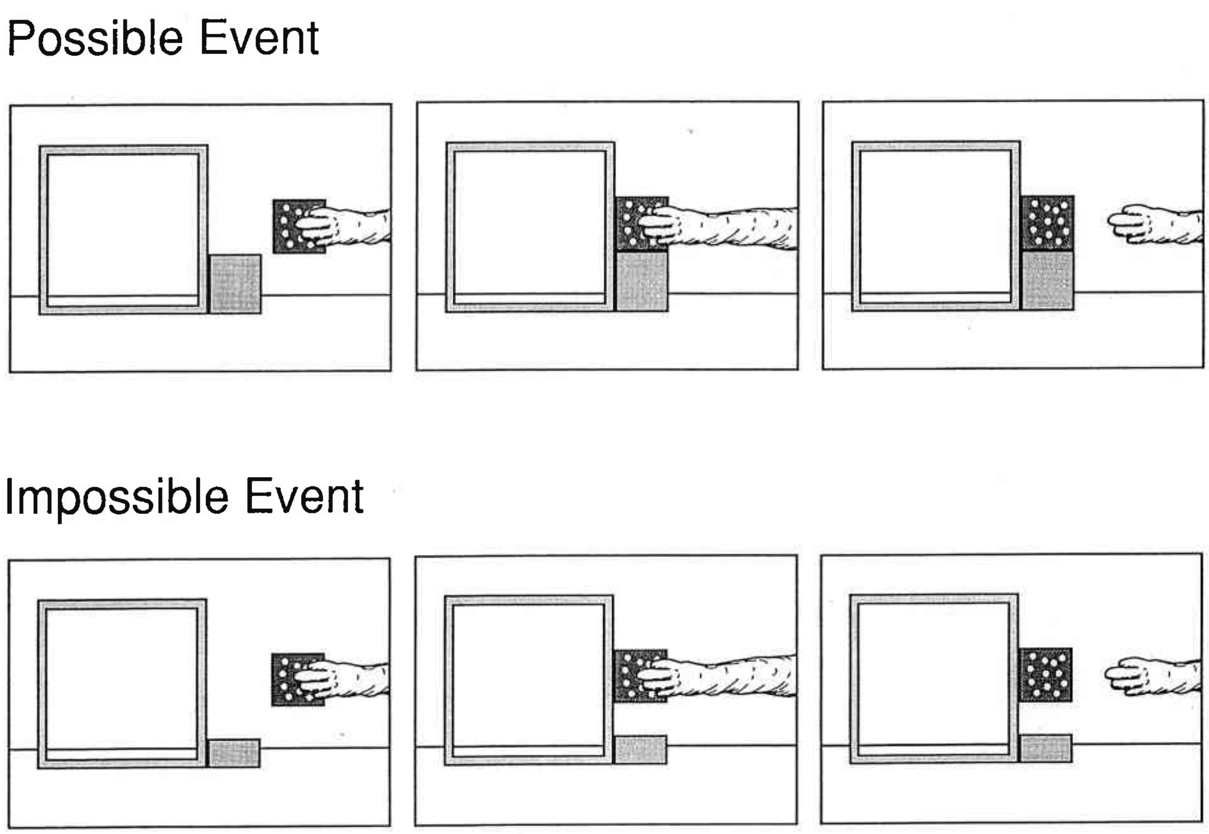

FIGURE 11.4 Test events used in Baillargeon, Raschke, and Needham (1994).

quately supported when it contacted only the side of the open platform and hence expected the box to fall in the impossible event and were surprised that it did not. A control condition in which the hand retained its grasp on the box provided evidence for this interpretation: The infants in this condition tended to look equally at the two test events.

In contrast to the female infants, the male infants in the experimental condition tended to look equally at the impossible and the possible events, as though they believed that the box was adequately supported in both events. Because female infants mature slightly faster than male infants (e.g., Haywood, 1986; Held, in press), gender-related differences such as the one described here are not uncommon in infancy research (e.g., Baillargeon and DeVos, 1991). Given this evidence, it is likely that, when tested with the same experimental procedure, slightly younger female infants (i.e., infants aged 3½ or 4 months) would perform like the 4½-month-old male infants, and slightly older male infants (i.e., infants aged 5 or 5½ months) would perform like the 4½-month-old female infants. An experiment is currently under way to confirm this last prediction.

The results of the last experiment indicated that by 4½ months of age, infants have begun to realize that a box can be stable when placed on but not against a platform. Our next experiment examined whether infants are aware that, in judging the box's stability, one must consider not only the *type* but also the *amount* of contact between the box and the platform (Baillargeon, Needham, and DeVos, 1992). Subjects were 5½- and 6½-month-old infants. The infants watched test events in which a gloved hand pushed a box from left to right along the top of a platform (figure 11.5). In the possible event, the box was pushed until its leading edge reached the end of the platform. In the impossible event, the box was pushed until only the left 15% of its bottom surface remained on the platform. Prior to the test events, the infants saw similar habituation events except that a much longer platform was used so that the box was always fully supported.

The results indicated that the 5½-month-old infants tended to look equally at the two test events, as though they judged that the box was adequately supported in both events. In contrast, the 6½-month-old infants looked reliably longer at the impossible than at the possible event, suggesting that they realized that the box was inadequately supported when only its corner rested on the platform and thus were surprised by the impossible event in which the box did not fall. A control condition in which the hand fully grasped the box provided evidence for this interpretation. In a subsequent experiment (Baillargeon, Needham, and DeVos, 1992), we found that 6½-month-old infants expected the box to be stable when 70%, as opposed to 15%, of its bottom surface rested on the platform.

Together, the results of the experiments reported in this section suggest the following developmental sequence: By 3 months of age, if not before, infants expect the box to fall if it loses contact with the platform and to remain stable otherwise. At this stage, *any* contact between the box and the platform is deemed sufficient to ensure the box's stability. At least two developments take place between 3 and 6½ months of age. First, infants become aware that the locus of contact between the box and the platform must be taken into account when judging the box's stability. Infants initially assume that the box will remain stable if placed either on or against the platform. By 4½ to (presumably) 5½ months of age, however, infants come to distinguish between the two types of contact and recognize that only the former ensures support. The second development is that infants begin to appreciate that the amount of contact between the box and the platform affects the box's stability. Initially, infants believe that the box will be stable even if only a small portion (e.g., the left 15%) of its bottom surface rests on the platform. By 6½ months of age, however, infants expect the box to fall unless a significant portion of its bottom surface (e.g., 70%) lies on the platform.

One way of describing this developmental sequence is that, when learning about the support relation between two objects, infants first form an initial concept centered on a contact/no-contact distinction. With further experience, this initial concept is progressively revised. Infants identify first a discrete (type of contact) and later a continuous (amount of contact) variable and incorporate these variables into their initial concept, resulting in more successful predictions over time.

Knowledge about Collision Phenomena Our research on infants' reasoning about collision phenomena has focused on simple problems involving a moving and a stationary object. Our first experiment (Kotovsky and Baillargeon, 1994b) asked whether 2½-month-old infants expect a stationary object to be displaced when hit by a moving object. The infants in the experiment

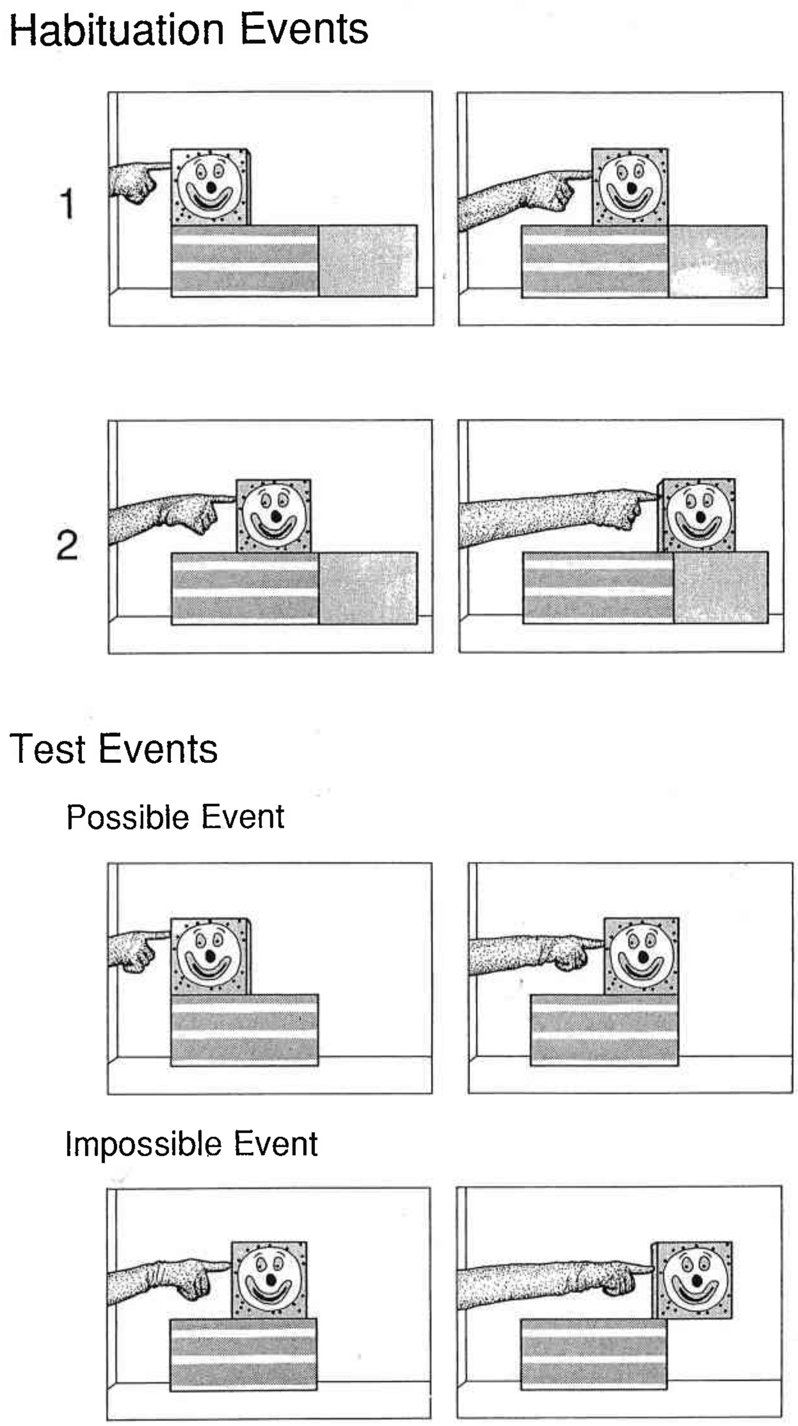

FIGURE 11.5 Test events used in Baillargeon, Needham, and DeVos, (1992).

sat in front of an inclined ramp; to the right of the ramp was a narrow track (figure 11.6). The infants were first habituated to a large cylinder that rolled down the ramp; small stoppers prevented the cylinder from rolling past the ramp. Following habituation, a large wheeled toy bug was placed on the track. In the possible event, the bug was placed 10 cm from the ramp, and it was *not* hit by the cylinder and thus remained stationary after the cylinder rolled down the ramp. In the impossible event, the bug was placed

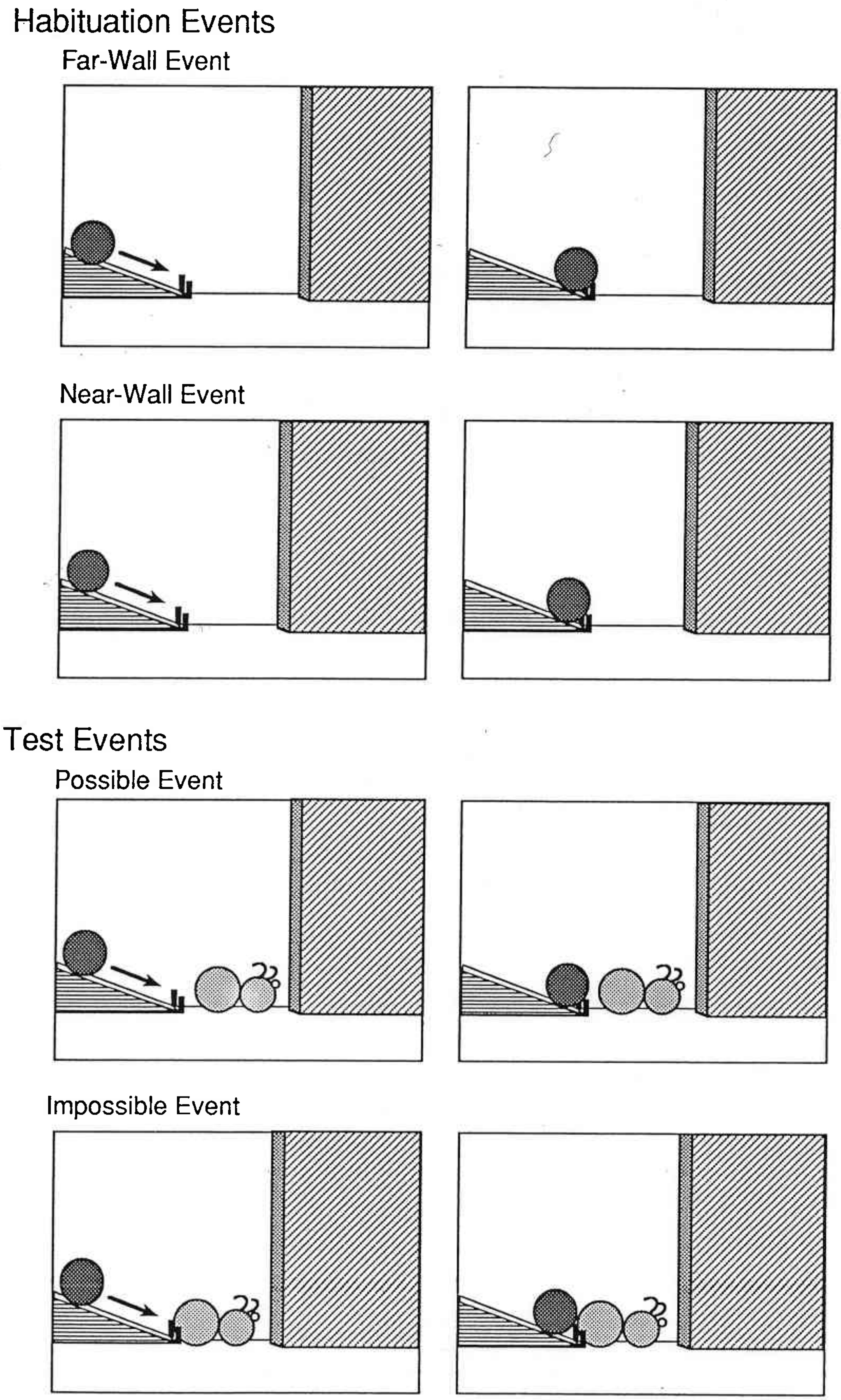
Habituation Events
Far-Wall Event
Near-Wall Event
Test Events
Possible Event
Impossible Event

FIGURE 11.6 Test events used in Kotovsky and Baillargeon (1994b).

directly at the bottom of the ramp, and it *was* hit by the cylinder but again remained stationary. Adult subjects typically expect the bug to roll down the track when hit by the cylinder; the experiment thus tested whether $2\frac{1}{2}$-month-old infants would share the same expectation as adults and would be surprised by the impossible event in which the bug remained stationary.

A second group of $2\frac{1}{2}$-month-old infants was tested in a control condition identical to the experimental condition with one exception. In each test event, the right wall of the apparatus was adjusted so that it stood against the front end of the bug, preventing its displacement (recall that, according to the results of Spelke et al., 1992, $2\frac{1}{2}$-month-old infants recognize that an object cannot move through the space occupied by another object).[2]

The infants in the experimental condition looked reliably longer at the impossible than at the possible event, whereas the infants in the control condition tended to look equally at the two events they were shown. Together, these results indicated that the infants in the experimental condition expected the bug to be displaced when hit by the cylinder and hence were surprised by the impossible event in which the bug remained stationary. The results of this first experiment indicated that, by $2\frac{1}{2}$ months of age, infants expect a stationary object to be displaced when hit by a moving object.

Our next experiment asked whether infants could use the size of the moving object to predict how far the stationary object should be displaced (Kotovsky and Baillargeon, 1994a, in press). One group of $6\frac{1}{2}$-month-

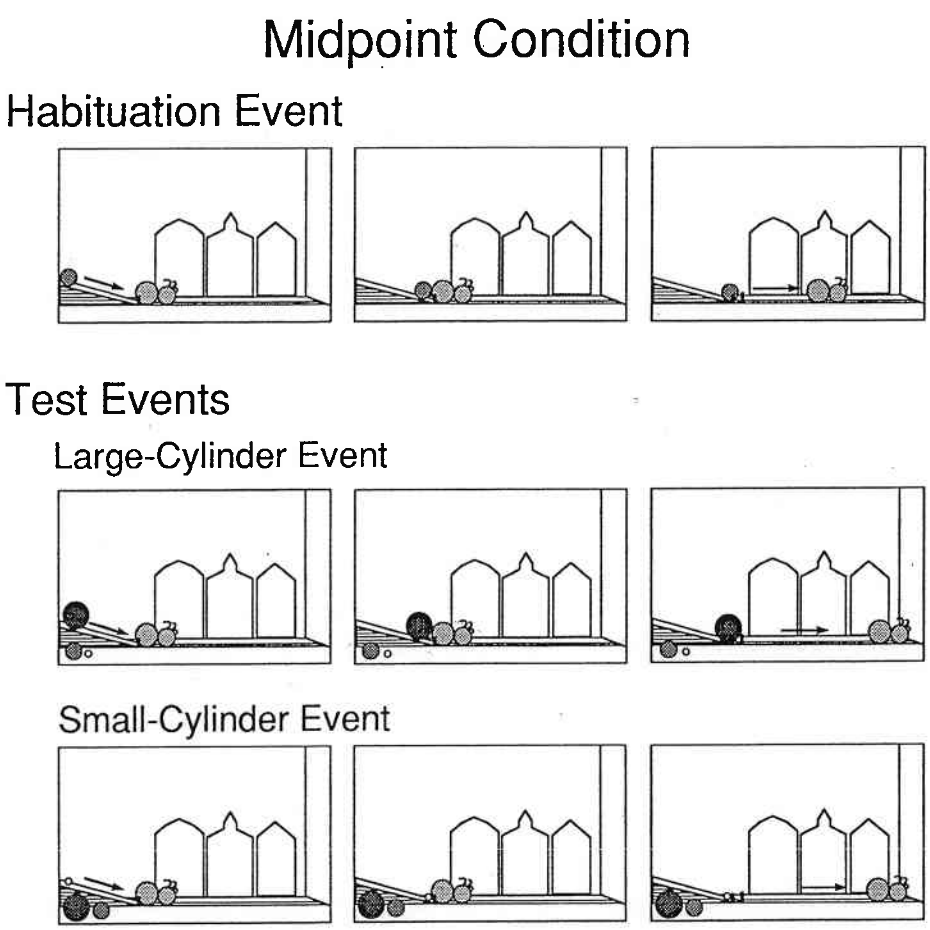

FIGURE 11.7 Test events used in the midpoint condition in Kotovsky and Baillargeon (1994a, experiment 1).

old infants (midpoint condition) was habituated to a blue, medium-size cylinder that rolled down a ramp and hit a toy bug, causing it to roll to the middle of a track (figure 11.7). Two new cylinders were introduced in the test events: a yellow cylinder that was larger than the habituation cylinder, and an orange cylinder that was smaller than the habituation cylinder. Both cylinders caused the bug to travel farther than in the habituation event: The bug stopped only when it reached the end of the track and hit the right wall of the apparatus.

When asked how far the bug would roll when hit by any one cylinder, adult subjects were typically reluctant to hazard a guess: They were aware that the length of the bug's trajectory depended on a host of factors (e.g., the weight of the cylinder and bug, the smoothness of the ramp and track, and so on) about which they had no information. After observing that the bug rolled to the middle of the track when hit by the medium cylinder, however, adult subjects readily predicted that the bug would roll farther with the larger and less far with the smaller cylinder and were surprised when this last prediction was violated.[3] The experiment thus tested whether $6\frac{1}{2}$-month-old infants, like adults, would understand that the size of the cylinder affected the length of the bug's displacement and would be able to use the information conveyed in the habituation event to calibrate their predictions about the test events.

A second group of infants (endpoint condition) was tested in a condition identical to the midpoint condition except that they were given a different calibration point in the habituation event. As shown in figure 11.8, the medium cylinder now caused the bug to roll to the end of the track, just as in the test events.

After seeing that the bug rolled to the end of the track when hit by the medium cylinder, adult subjects expected the bug to do the same with the large cylinder

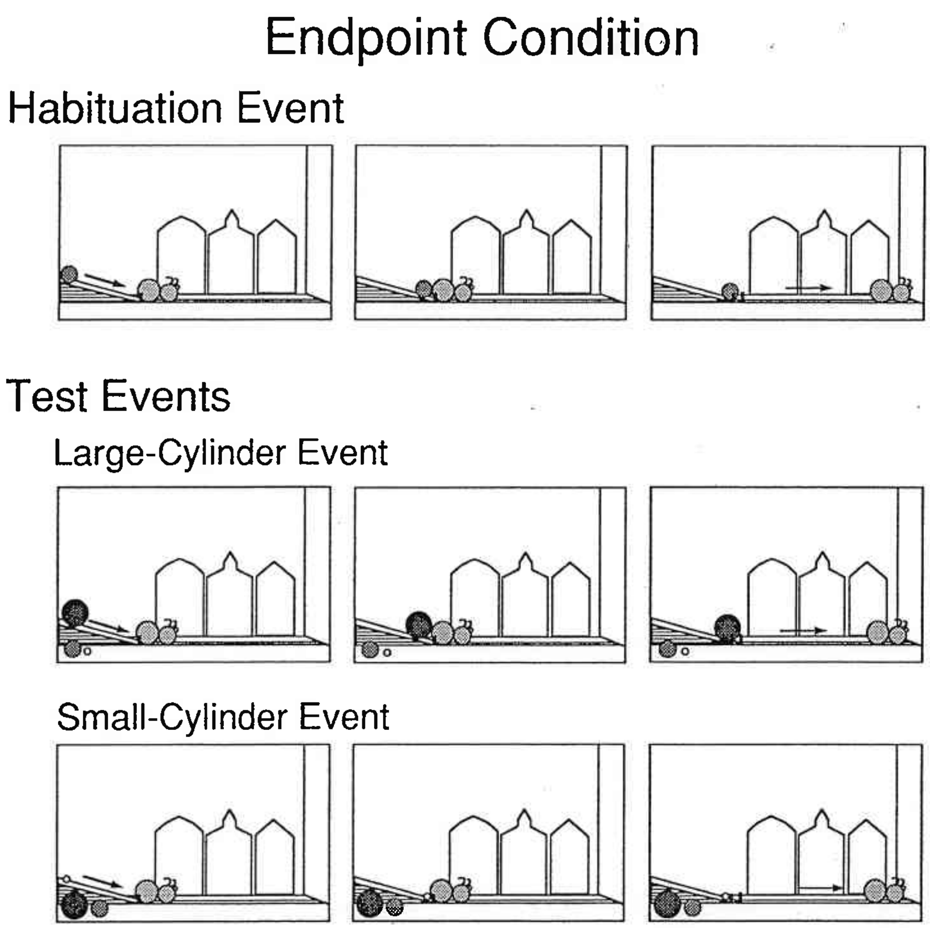

FIGURE 11.8 Test events used in the endpoint condition in Kotovsky and Baillargeon (1994a, experiment 1).

and were not surprised to see the bug do the same with the small cylinder (subjects simply concluded that the track was too short to show effects of cylinder size). The experiment thus tested whether $6\frac{1}{2}$-month-old infants, like adults, would perceive both of the endpoint condition test events as possible.

The results indicated that the infants in the midpoint condition looked reliably longer at the small-cylinder than at the large-cylinder event, whereas the infants in the endpoint condition tended to look equally at the two events. Together, these results indicated that the infants were aware that the size of the cylinder should affect the length of the bug's trajectory and used the habituation event to calibrate their predictions about the test events. After watching the bug travel to the middle of the track when hit by the medium cylinder, the infants were surprised to see the bug travel farther with the smaller but not the larger cylinder. In contrast, after watching the bug travel to the end of the track with the medium cylinder, the infants were not surprised to see the bug do the same with either the small or the large cylinder.

In a subsequent experiment, $5\frac{1}{2}$-month-old infants were tested using the same procedure (Kotovsky and Baillargeon, 1994a). The performance of the female infants was identical to that of the $6\frac{1}{2}$-month-old infants. The male infants, in contrast, tended to look equally at the test events in both the midpoint and the endpoint conditions. At least two interpretations could be advanced for this negative finding. One was that the male infants were still unaware that the size of the cylinder should affect the length of the bug's displacement. The other interpretation was that the male infants had difficulty remembering how far the bug traveled in the habituation event and hence could not make use of this information to predict what should happen in the small-cylinder and large-cylinder events.

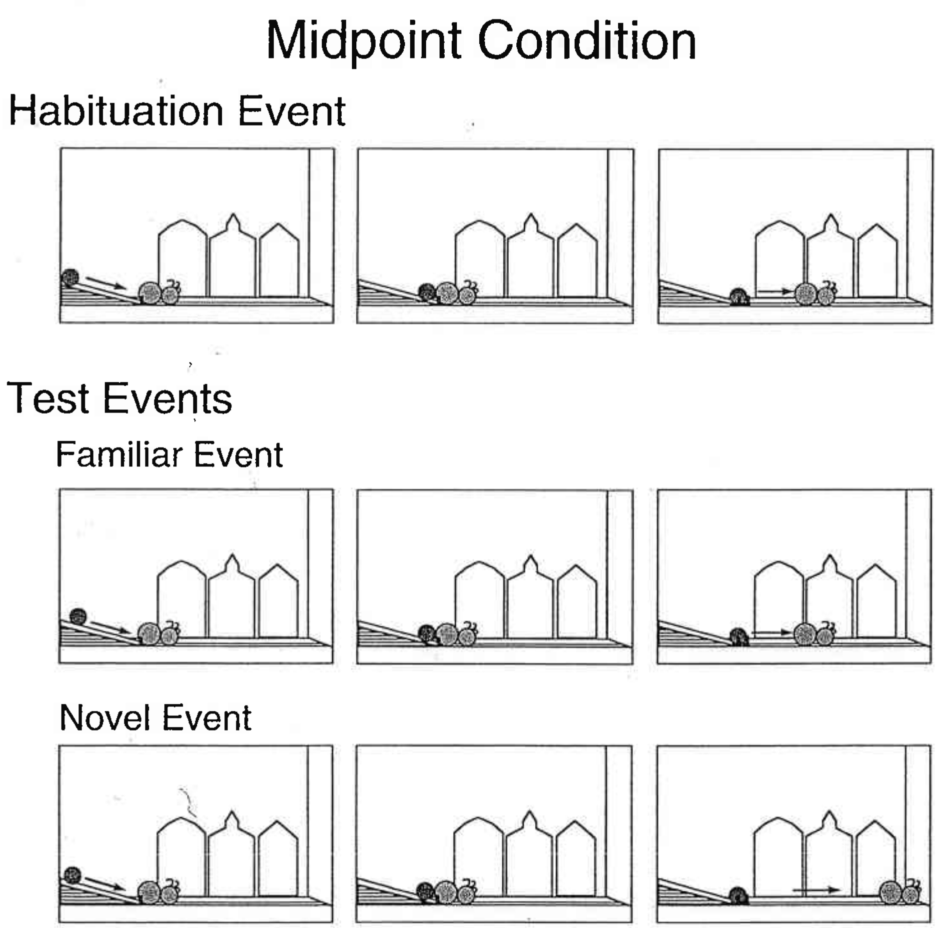

FIGURE 11.9 Test events used in the midpoint condition in Kotovsky and Baillargeon (1994a, experiment 3).

To examine this second interpretation, two groups of $5\frac{1}{2}$-month-old male infants were tested in a simple memory experiment (Kotovsky and Baillargeon, 1994a). The infants in the midpoint condition, as before, were habituated to the medium cylinder rolling down the ramp and hitting the bug, causing it to roll to the middle of the track (figure 11.9). Following habituation, the infants saw two test events. One (familiar test event) was identical to the habituation event. In the other event (novel test event), the medium cylinder now caused the bug to roll to the end of the track. The infants in the endpoint condition saw similar habituation and test events, except that the bug rolled to the end of the track in the habituation event so that which test event was familiar and which was novel were reversed (figure 11.10).

The results revealed a significant overall preference for the novel over the familiar test event, indicating that the infants had no difficulty recalling how far the bug rolled in the habituation event. Such a finding, combined with the negative finding obtained in the last experiment, suggests this conclusion: After observing that the medium cylinder causes the bug to roll to the middle of the track, $5\frac{1}{2}$-month-old male infants expect the bug to do the same when hit by the *same* cylinder but have no expectation as to how far the bug should roll when hit by cylinders of different sizes. Infants seem unaware that they possess information they can use to reason about the novel cylinders.

Together, the results of these collision experiments point to the following developmental sequence: By $2\frac{1}{2}$ months of age, infants expect a stationary object to be displaced when hit by a moving object; however, they are not yet aware that the size of the moving object can be used to predict how far the stationary object will be displaced. If shown that a medium cylinder causes a bug to roll to the middle of a track, for example, infants have no expectation that the bug should travel farther

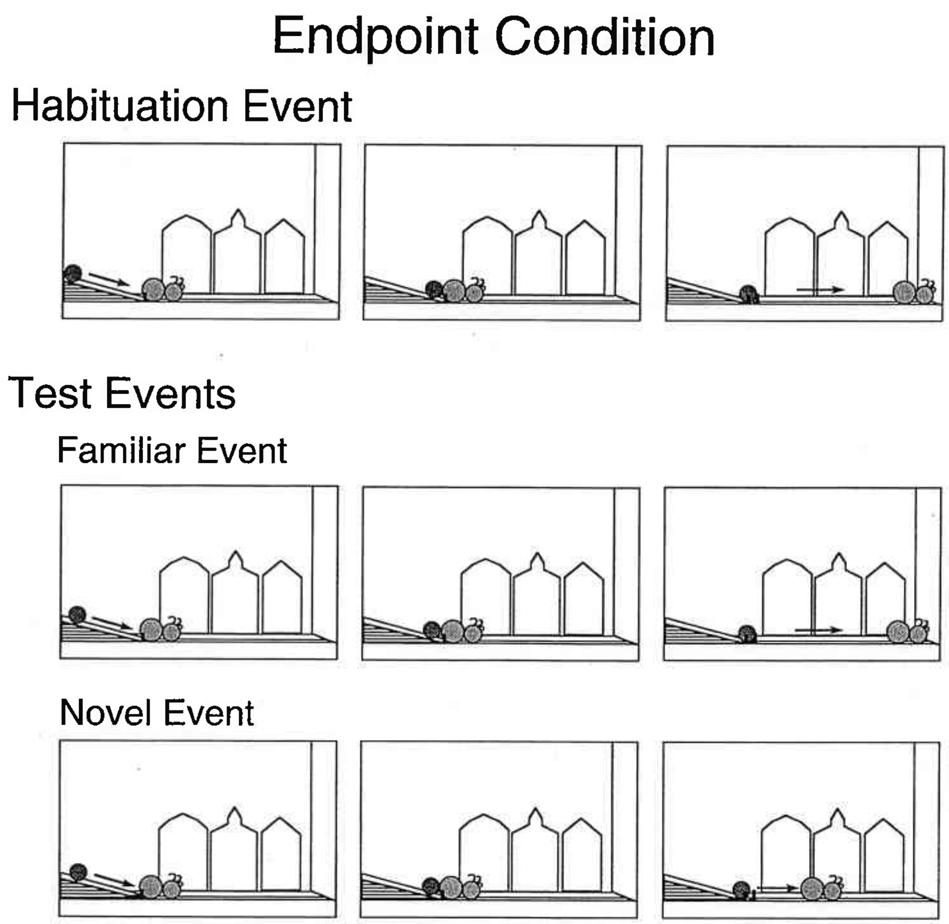

FIGURE 11.10 Test events used in the endpoint condition in Kotovsky and Baillargeon (1994a, experiment 3).

when hit by a larger cylinder and less far when hit by a smaller cylinder. By $5\frac{1}{2}$ to $6\frac{1}{2}$ months of age, however, infants recognize not only that a stationary object should be displaced when hit by a moving object but also that *how far* the stationary object is displaced depends on the size of the moving object.

One interpretation of these findings is that, when learning about collision events between a moving and a stationary object, infants first form an initial concept centered on an impact/no-impact distinction. With further experience, infants begin to identify variables that influence this initial concept. By $5\frac{1}{2}$ to $6\frac{1}{2}$ months of age, infants realize that the size of the moving object can be used to predict how far the stationary object will be displaced.

Knowledge about Unveiling Phenomena Our experiments on unveiling phenomena have involved problems in which a cloth cover is removed to reveal an object. Our first experiment examined whether $9\frac{1}{2}$-month-old infants realize that the presence (absence) of a protuberance in a cover signals the presence (absence) of an object beneath the cover (Baillargeon and DeVos, 1994a). At the start of the possible event, the infants saw two covers made of a soft, fluid fabric; the left cover lay flat on the floor of the apparatus, and the right cover showed a marked protuberance (figure 11.11). Next, two screens were pushed in front of the covers, hiding them from view. A hand then reached behind the right screen and reappeared first with the cover and then with a toy bear of the same height as the protuberance shown earlier. The impossible event was identical except that the location of the two covers at the start of the event was reversed, so that it should have been impossible for the hand to retrieve the bear from behind the right screen.

The infants looked reliably longer at the impossible than at the possible event, suggesting that they understood that the bear could have been hidden under the cover with a protuberance but not under the flat cover. This interpretation was supported by the results of a second condition in which the hand reached behind the left as opposed to the right screen so that the bear's position in the impossible and the possible events was reversed.

The results of this first experiment indicated that, by 9 months of age, infants can use the existence of a protuberance in a cloth cover to infer the existence of an object beneath the cover. Our next experiment (Baillargeon and DeVos, 1994a) investigated whether infants could also use the size of the protuberance to infer the size of the object under the cover (figure 11.12). At the start of the possible event, the infants saw two covers made of a soft fabric: on the left was a small cover with a small protuberance; on the right was a large cover with a large protuberance. (The small protuberance was 10.5 cm high and the large protuberance 22 cm high; the difference between the two was

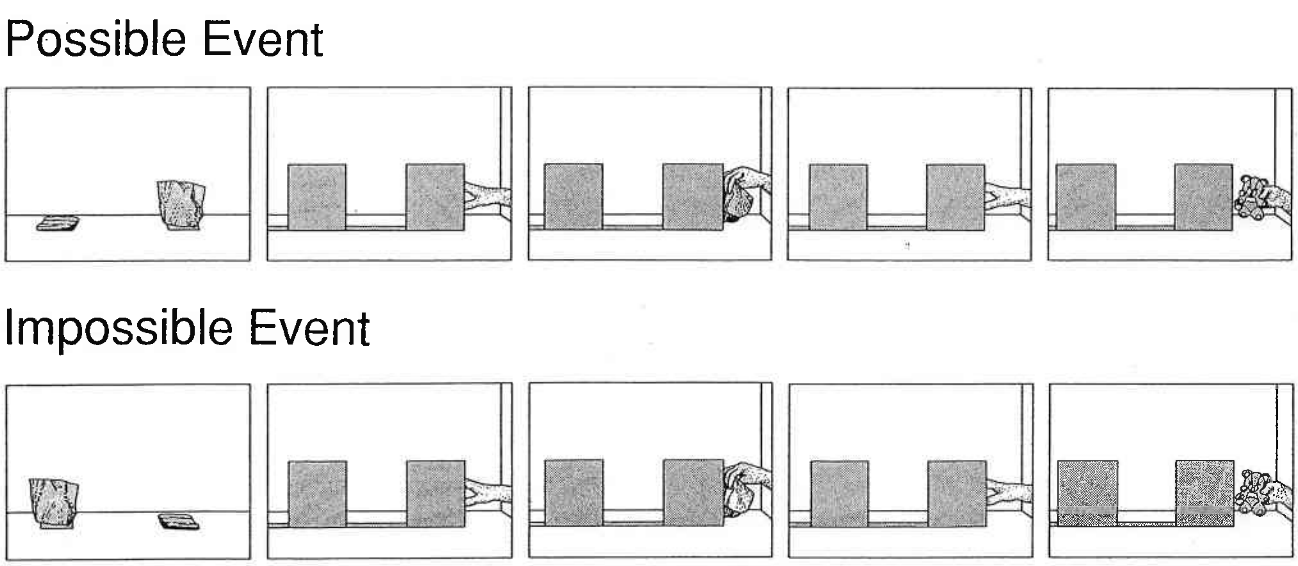

Figure 11.11 Test events used in Baillargeon and DeVos (1994a, experiment 1).

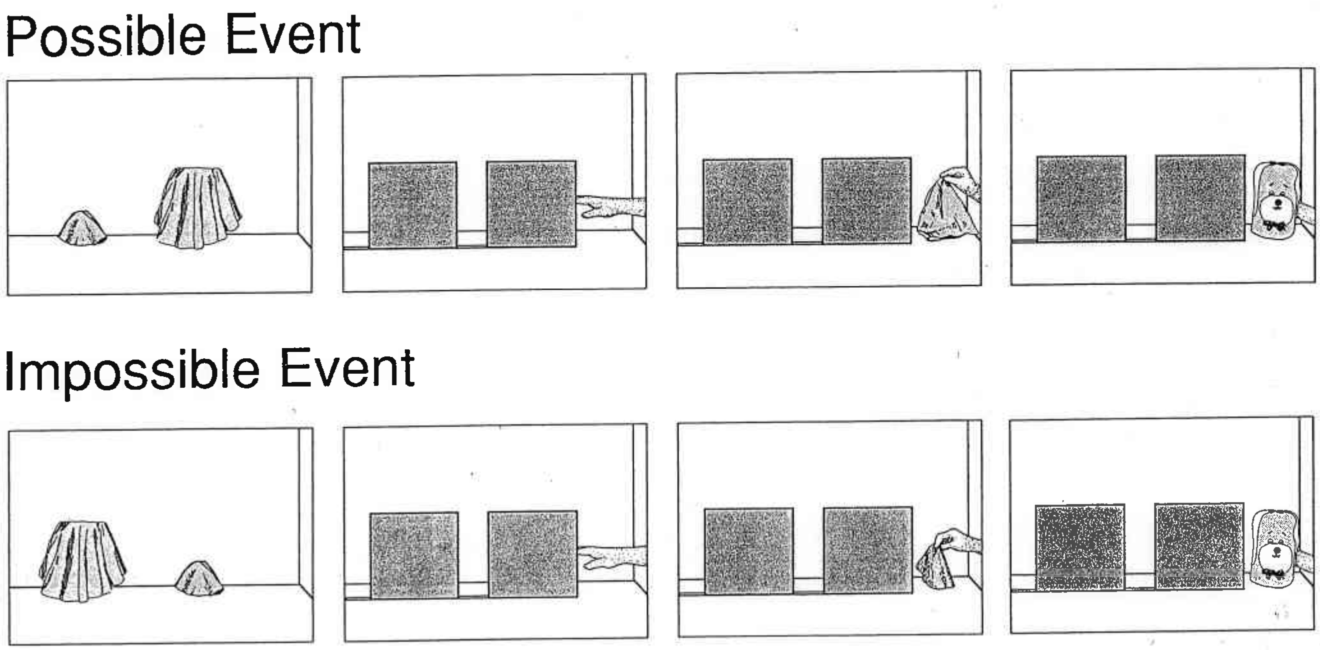

FIGURE 11.12 Test events used in Baillargeon and DeVos (1994a, experiment 3).

thus easily detectable.) Next, screens were pushed in front of the covers, and a gloved hand reached behind the right screen twice in succession, reappearing first with the cover and then with a large toy dog 22 cm tall. The impossible event was identical to the possible event except that the location of the two covers at the start of the event was reversed, so that the hand now appeared to retrieve the large dog from under the cover with the small protuberance.

Unlike the infants in the last experiment, the infants in this experiment tended to look equally at the impossible and at the possible events, suggesting that they believed that the large dog could have been hidden under the cover with either the small or the large protuberance. The same result was obtained in a subsequent experiment that made use of a slightly different procedure (Baillargeon and DeVos, 1994a). How should these negative findings be explained? At least two hypotheses could be proposed. One was that the infants were not yet aware that the size of the protuberance in each cover could be used to infer the size of the object hidden beneath the cover. The other explanation was that the infants recognized the significance of the protuberance's size but had difficulty remembering this information after the cover was hidden from view.

The results of another experiment provided evidence for the first of these two interpretations. The infants in this experiment (Baillargeon and DeVos, 1994b) were given a reminder of the size of the protuberance in the cover behind the screen (figure 11.13). Subjects were $9\frac{1}{2}$- and $12\frac{1}{2}$-month-old infants. At the start of the possible event, the infants saw the cover with the small protuberance; to the right of this cover was a second, identical cover. After a brief pause, the first cover was hidden by the screen; the second cover remained visible to the right of the screen. Next, the hand reached behind the screen's right edge and removed first the cover and then a small toy dog 10.5 cm in height. The hand held the small dog next to the visible cover, allowing the infants to compare their sizes directly. The impossible event was identical to the possible event, except that the hand retrieved the large toy dog from behind the screen.

The $12\frac{1}{2}$-month-old infants looked reliably longer at the impossible than at the possible event, suggesting that they realized that the small but not the large dog could have been hidden under the cover behind the screen. This interpretation was supported by the results of a control condition in which the infants simply saw each dog held next to the visible cover (as in the rightmost panels in figure 11.13); no reliable preference was found for the large-dog over the small-dog display.

In contrast to the $12\frac{1}{2}$-month-old infants, the $9\frac{1}{2}$-month-old infants tended to look equally at the impos-

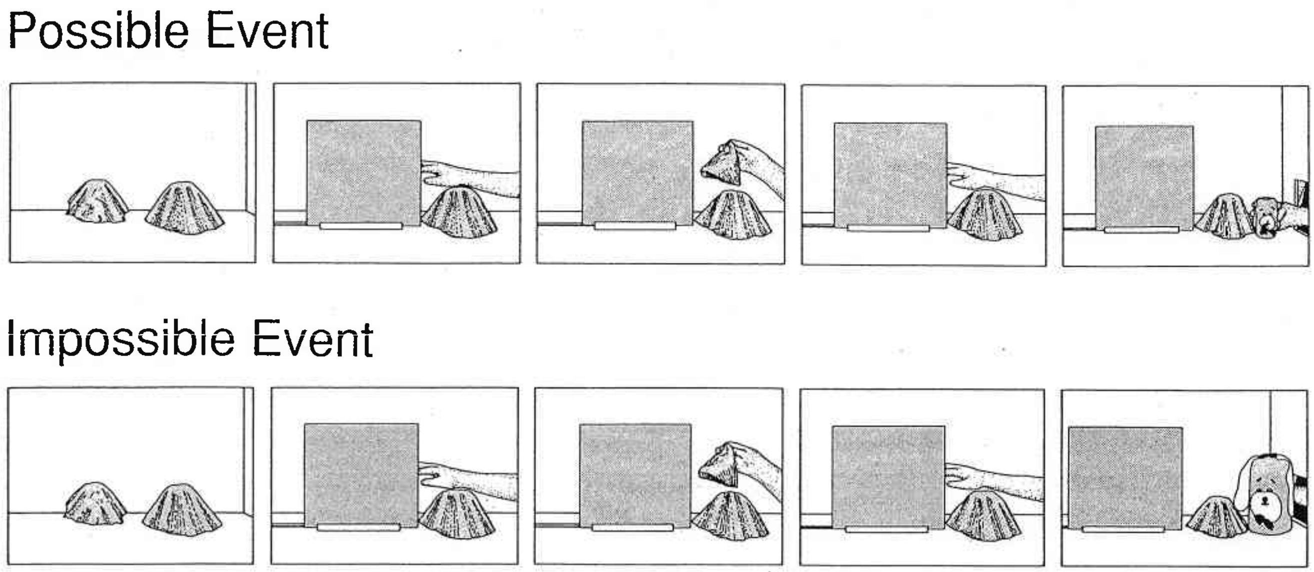

FIGURE 11.13 Test events used in Baillargeon and DeVos (1994b, experiment 2).

sible and the possible events. Thus, despite the fact that the infants had available a reminder—an exact copy—of the cover behind the screen, they still failed to show surprise at the large dog's retrieval. It might be argued that infants younger than $12\frac{1}{2}$ months of age are simply unable, when reasoning about hidden objects, to take advantage of reminders such as the visible cover. As will be seen later, however, even young infants can make use of visual reminders to make predictions concerning hidden objects.

The results summarized in this section suggest the following developmental sequence: By 9 months of age, infants realize that the existence of a protuberance in a cloth cover signals the existence of an object beneath the cover: They are surprised to see an object retrieved from under a flat cover but not from under a cover with a protuberance. However, infants are not yet aware that the size of the protuberance can be used to infer the size of the hidden object. When shown a cover with a small protuberance, they are not surprised to see either a small or a large object retrieved from under that cover. Furthermore, providing a reminder of the protuberance's size has no effect on infants' performance. Under the same conditions, however, $12\frac{1}{2}$-month-old infants show reliable surprise at the large object's retrieval.

One interpretation of these findings is that, when learning about unveiling phenomena, infants first form an initial concept centered on a protuberance/no-protuberance distinction. Later on, infants identify a continuous variable that affects this concept: They begin to appreciate that the size of the protuberance in the cover can be used to predict the size of the object hidden under the cover.

DISCUSSION How can the various developmental sequences described in this section be explained? As was mentioned earlier, our assumption is that these sequences reflect not the gradual unfolding of innate beliefs but the application of highly constrained, innate learning mechanisms to available data. In this approach, the problem of explaining the age at which specific initial concepts and variables are understood is that of determining what data—observations or manipulations—are necessary for learning and when these data become available to infants.

To illustrate, consider the developmental sequence revealed in our support experiments. One might propose that 3-month-old infants have already learned that objects fall when released in midair (Needham and Baillargeon, 1994) because this expectation is consistent with countless observations (e.g., watching their caretakers drop peas in pots, toys in baskets, clothes in hampers) and manipulations (e.g., noticing that their pacifiers fall when they open their mouths) available virtually from birth.

Furthermore, one might speculate that infants do not begin to recognize until $4\frac{1}{2}$ months (Baillargeon, Raschke, and Needham, 1994) what type of contact is needed between objects and their supports because it is not until this age that infants have available pertinent data from which to abstract this variable. Researchers have found that unilateral, visually guided reaching emerges at approximately 4 months of age (e.g., White, Castle, and Held, 1964). With this newfound ability, infants may have the opportunity to place objects deliberately against other objects and to observe the consequences of these actions. The gender-related difference revealed in our experiment, in this account, would be traceable to female infants engaging in these manipulations slightly ahead of the male infants.

In a similar vein, one could suggest that it is not until $6\frac{1}{2}$ months that infants begin to appreciate how much contact is needed between objects and their supports (Baillargeon, Needham, and DeVos, 1992) because, once again, it is not until this age that infants have available data from which to learn such a variable. Investigators have reported that the ability to sit without support emerges at approximately 6 months of age; infants then become able to sit in front of tables (e.g., on a parent's lap or in a high chair) with their upper limbs and hands relieved from the encumbrance of postural maintenance and thus free to manipulate objects (e.g., Rochat and Bullinger, in press). For the first time, infants may have the opportunity to deposit objects on tables and to note that objects tend to fall unless a significant portion of their bottom surfaces is supported.

In the natural course of events, infants would be unlikely to learn about variables such as type or amount of contact from visual observation alone, because caretakers rarely deposit objects against vertical surfaces or on the edges of horizontal surfaces. There is no a priori reason, however, to assume that infants could not learn such variables if given appropriate observations. We are currently planning "teaching" experiments to explore this possibility.

Second pattern: Use of qualitative and quantitative strategies

In the preceding section we proposed that, when learning about a novel physical phenomenon, infants first develop an all-or-none initial concept and later identify discrete and continuous variables that affect this concept. The second developmental pattern suggested by current evidence concerns the strategies infants use when reasoning about continuous variables. Following the terminology used in computational models of everyday physical reasoning (e.g., Forbus, 1984), a strategy is said to be *quantitative* if it requires infants to encode and use information about absolute quantities (e.g., object A is this large or has traveled this far from object B, where *this* represents some absolute measure of A's size or distance from B). In contrast, a strategy is said to be *qualitative* if it requires infants to encode and use information about relative quantities (e.g., object A is larger than or has traveled farther than object B). After identifying a continuous variable, infants appear to succeed in reasoning about the variable qualitatively before they succeed in doing so quantitatively.

To illustrate the distinction between infants' use of qualitative and quantitative strategies, I will report experiments on the development of infants' ability to reason about collision phenomena (conducted with Laura Kotovsky), unveiling phenomena (conducted with Julie DeVos), and arrested-motion phenomena.

Reasoning about Collision Phenomena Earlier in this chapter (and in Kotovsky and Baillargeon, 1994a), I reported that $6\frac{1}{2}$-month-old infants and $5\frac{1}{2}$-month-old female infants were surprised, after observing that a medium-size cylinder caused a bug to roll to the middle of a track, to see the bug roll farther when hit by a smaller but not a larger cylinder (see figure 11.7). These and other findings indicated that the infants were aware that the size of the cylinder affected the length of the bug's trajectory.

In these experiments, each test event began with a pretrial in which the small, medium, and large cylinders lay side by side at the front of the apparatus. A gloved hand tapped on the cylinder to be used in the event (e.g., the small cylinder in the small-cylinder event). After the computer signaled that the infant had looked at the cylinder for 4 cumulative seconds, the hand grasped the cylinder and deposited it at the top of the ramp to begin the test event. The pretrial was included to enable the infants to compare directly the sizes of the cylinders.

In a subsequent experiment (Kotovsky and Baillargeon, 1994c), $6\frac{1}{2}$- and $7\frac{1}{2}$-month-old infants saw habituation and test events identical to those used in the midpoint condition in our initial experiments, with one exception: Only one cylinder was present in the apparatus in each event. During the pretrial preceding each test event, the gloved hand again tapped on the cylinder, but the other cylinders were absent so that the infants were no longer able to compare the cylinders' sizes visually. Under these conditions, the $6\frac{1}{2}$-month-old infants no longer showed surprise when the small cylinder caused the bug to roll to the end of the track; only the $7\frac{1}{2}$-month-old infants looked reliably longer at the impossible than at the possible event.

Our interpretation of these results is that, at $5\frac{1}{2}$ to $6\frac{1}{2}$ months of age, infants are able to reason about the cylinder's size only qualitatively: They can predict the effect of modifications in the cylinder's size only when they are able to encode such modifications in relative terms (e.g., "This cylinder is smaller than the one next to it, which was used in the last trial"). When forced to encode and compare the absolute sizes of the cylinders, because the cylinders are never shown side by side, the infants fail the task. By $7\frac{1}{2}$ months of age, however, infants have already overcome this initial limitation and succeed in our task even when they must rely on their representation of the absolute size of each cylinder to do so.[4]

Reasoning about Unveiling Phenomena Earlier in this chapter (and in Baillargeon and DeVos, 1994b), I reported that $12\frac{1}{2}$-month-old infants were surprised to see a large but not a small dog retrieved from under a cover with a small protuberance (see figure 11.13). These and control results indicated that the infants were aware that the size of the protuberance in the cover could be used to infer the size of the object hidden under the cover.

In our initial experiment, the infants were tested with a second, identical cover present to the right of the screen. Each dog, after it was retrieved from behind the screen, was held next to the visible cover, allowing the infants to compare in a single glance the size of the dog to that of the cover. In a subsequent experiment (Baillargeon and DeVos, 1994b), $12\frac{1}{2}$- and $13\frac{1}{2}$-month-old infants were tested with the same test events, except that only one cover was present: The infants no longer were provided with a second cover to remind them of the size of the cover behind the screen (figure 11.14). Under these conditions, only the $13\frac{1}{2}$-month-old infants looked reliably longer at the impossible than at the possible event, suggesting that they were surprised to see the large but not the small dog retrieved from the cover behind the screen. This interpretation was supported by a control condition in which a cover with a large rather than a small protuberance stood behind the screen.

The results of this last experiment suggested that the $12\frac{1}{2}$-month-old infants could not succeed at our task without a reminder of the size of the cover behind the screen. In our next experiment, we examined whether infants would remain successful if a second, identical

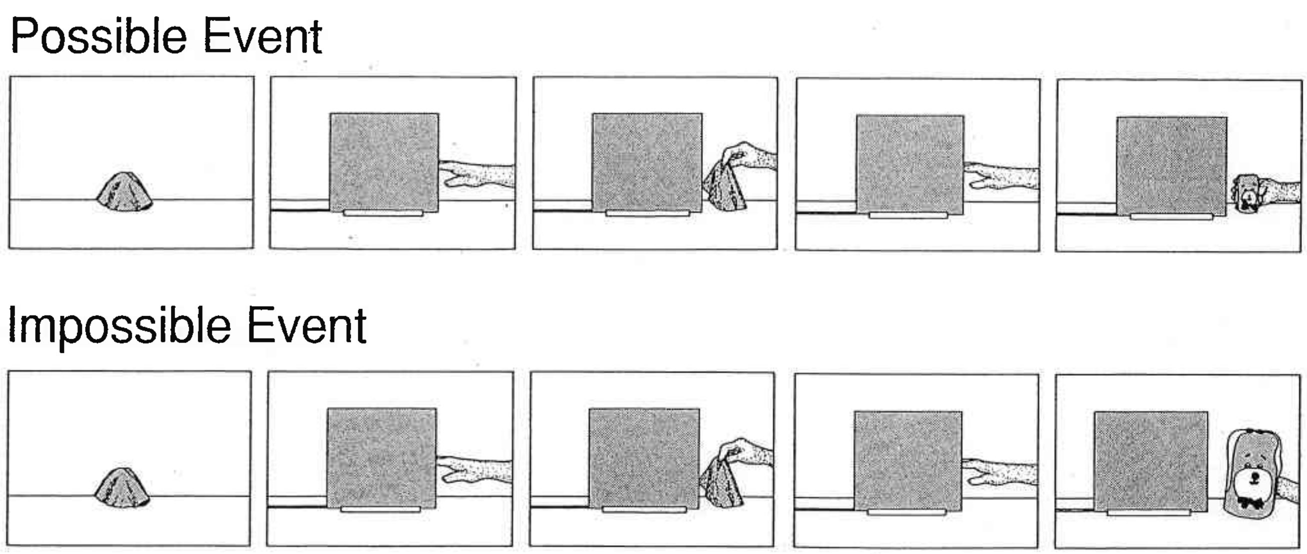

Figure 11.14 Test events used in Baillargeon and DeVos (1994b, experiment 1).

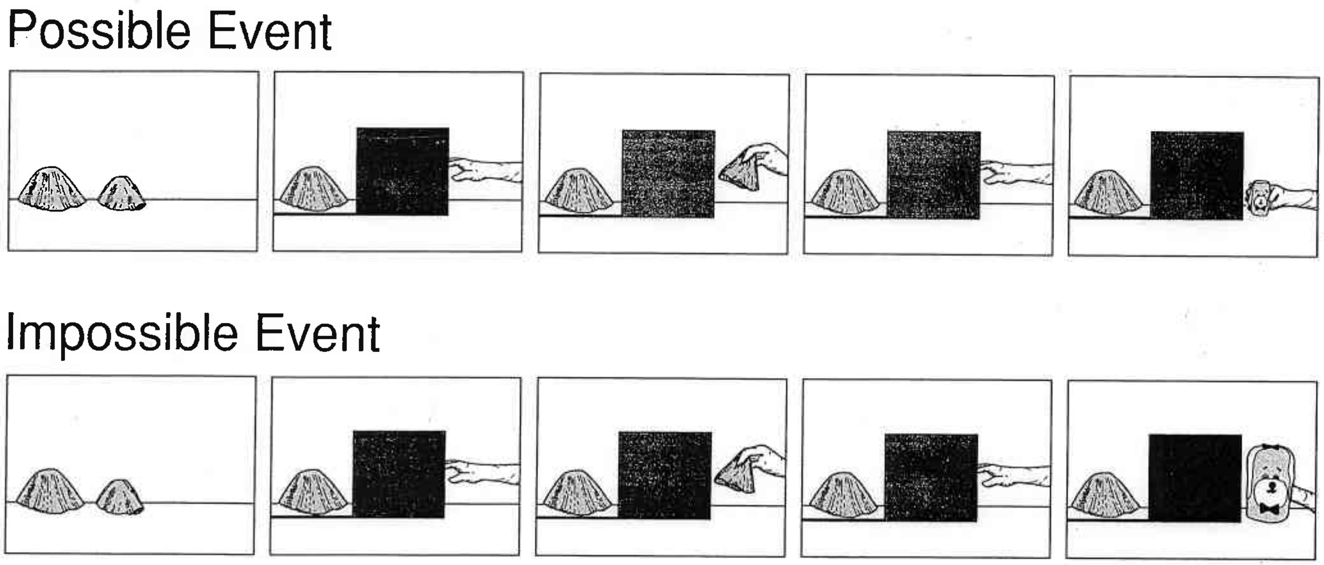

Figure 11.15 Test events used in Baillargeon and DeVos (1994b, experiment 3).

cover was again included in the test displays but was placed to the left rather than to the right of the screen (figure 11.15). The infants still had in their visual fields an exact copy of the hidden cover; however, they were no longer able to compare in a single glance the size of each dog to that of the visible cover. The results were once again negative: The infants failed to show surprise at the large dog's retrieval.

Together the results of these experiments suggest that, at $12\frac{1}{2}$ months of age, infants are able to reason only qualitatively about the size of the protuberance in the cover: They can determine which dog could have been hidden under the cover only if they are able to compare, in a single glance, the size of the dog to that of a second, identical cover (e.g., "The dog is bigger than the cover"). When infants are forced to represent the absolute size of the protuberance in the cover, they fail the task. By $13\frac{1}{2}$ months of age, however, infants have already progressed beyond this initial limitation; they no longer have difficulty representing the absolute size of the protuberance and comparing it to that of each dog.

Reasoning about Arrested-motion Phenomena Our research on arrested-motion phenomena has focused on problems involving a large box placed in the path of a rotating screen. One experiment examined $4\frac{1}{2}$-month-old infants' ability to use the height and location of the box to predict at what point the rotating screen would reach the box and stop (Baillargeon, 1991). At the start of each habituation event (figure 11.16), the infants saw a screen that lay flat against the floor of the apparatus, toward them; the screen then rotated 180° about its distant edge until it lay flat against the apparatus floor, toward the back wall. Following habituation, a box was placed behind the screen; this box was progressively occluded as the screen rotated upward. In the possible event, the screen rotated until it reached the occluded box (112° arc). In the impossible event, the screen stopped only after it rotated through the top 80% of the space occupied by the box (157° arc)—to adults, an extreme and easily detectable violation.

A second group of infants (two-box condition) saw the same test events as the infants in the first (one-box) condition, with one exception: A second, identical box was placed to the right of and in the same fronto-parallel plane as the box behind the screen (figure 11.17). The second box stood out of the screen's path and thus remained visible throughout the test events. In the possible event, the screen stopped when aligned with the top of the second box; in the impossible event, the screen rotated past the top of the visible box.

The infants in the two-box condition looked reliably longer at the impossible than at the possible event, suggesting that they realized that the screen's 157°

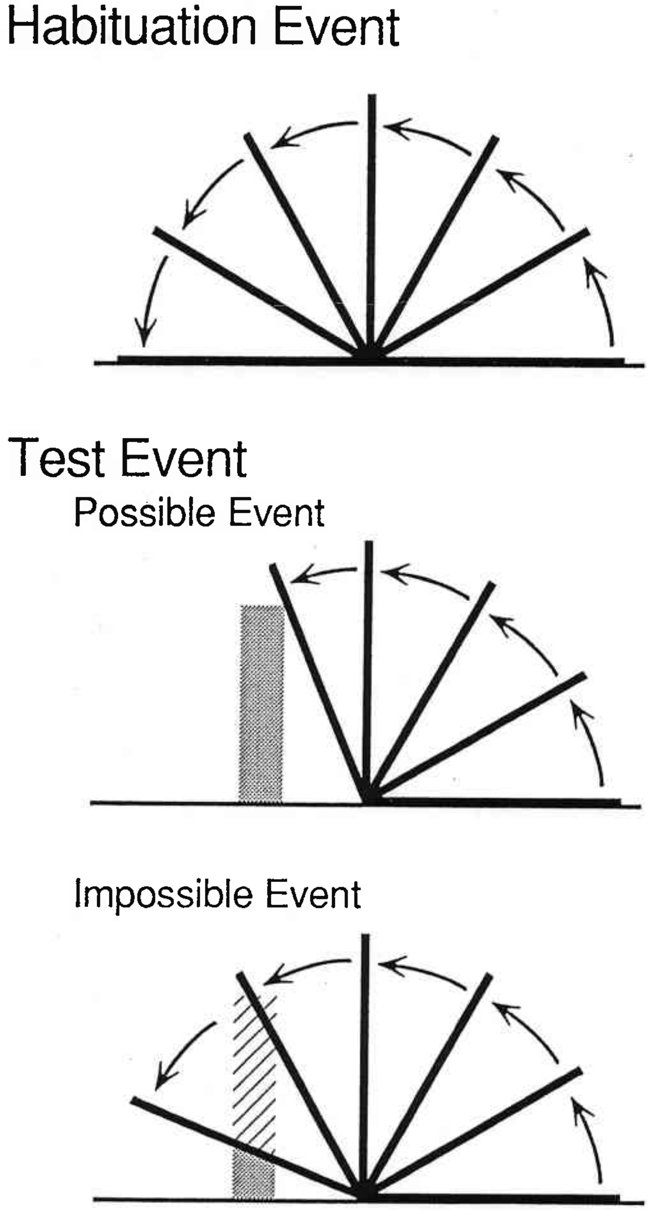

FIGURE 11.16 Test events used in the one-box condition in Baillargeon (1991, experiment 2). Side view.

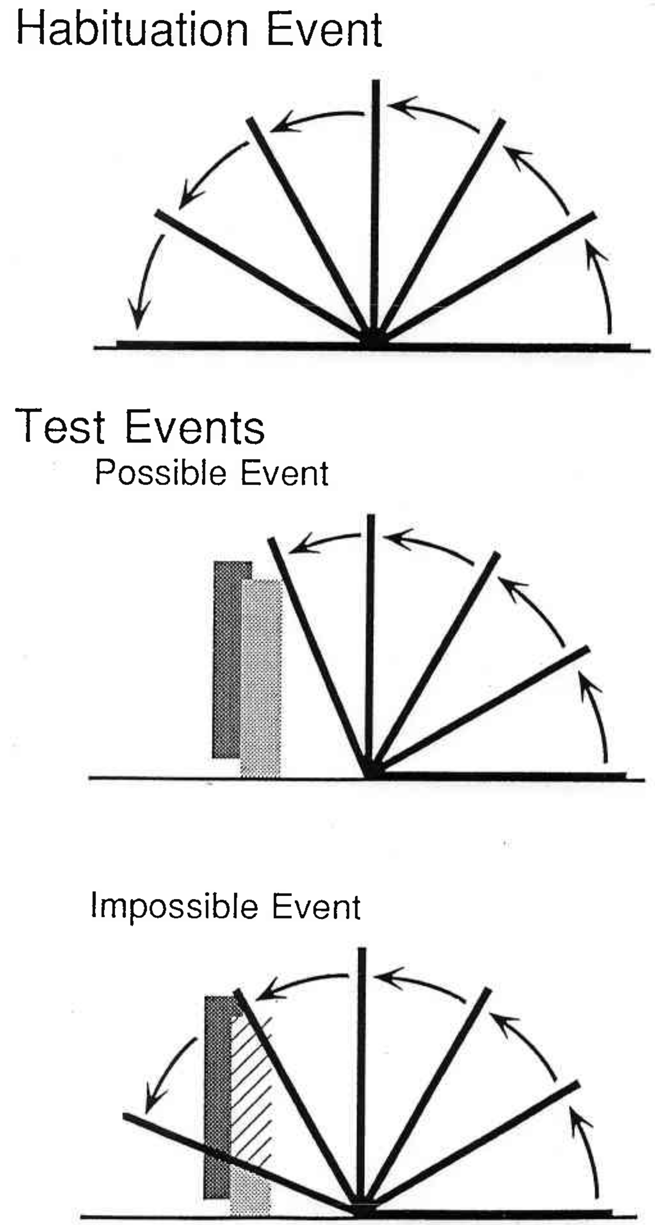

FIGURE 11.17 Test events used in the two-box condition in Baillargeon (1991, experiment 4). Side view.

stopping point was inconsistent with the height and location of the occluded box. This interpretation was supported by a control condition in which the box behind the screen was removed; when only the box to the right of the screen was present, the infants tended to look equally at the events.

In contrast to the infants in the two-box condition, the infants in the one-box condition tended to look equally at the impossible and the possible events, as though they judged both the 112°- and the 157°-screen stopping points to be consistent with the box's height and location. Together, the results of the one- and two-box conditions indicated that the infants were aware that the height and location of the box behind the screen could be used to predict at what point the screen would stop but could detect the 80% violation shown in the impossible event only when provided with a copy of the occluded box.

A subsequent experiment revealed that, not only did $4\frac{1}{2}$-month-old infants require the presence of a second box to detect the 80% violation, but this box had to be placed in the same frontoparallel plane as the occluded box (Baillargeon, 1991). When the second box was placed to the right but 10 cm in front of the box behind the screen, the infants no longer showed surprise at the screen's 157° stopping point (figure 11.18). In this experiment, the infants still had a reminder of the occluded box's height; however, they could no longer use a visual comparison strategy to solve the task. When the two boxes were in the same frontoparallel plane, as in the first experiment, all the infants needed to do to solve the task was to compare the height of the screen (at its stopping point) to that of the second box. When the second box was in front of the occluded box, however, this alignment strategy was no longer valid, because the screen rotated past the top of the second box in both the possible and the impossible events.

The results of these experiments thus paralleled those obtained with $12\frac{1}{2}$-month-old infants in the unveiling experiments summarized in the last section (Baillargeon and DeVos, 1994b). Recall that those infants were able to judge which dog could have been hidden under the cover behind the screen only when they could compare, in a single glance, the size of each dog to that of a second, identical cover. The infants failed the task when no second cover was used or the location of the second cover did not allow direct visual comparison with each dog.

In a final experiment (Baillargeon, 1991), $6\frac{1}{2}$-month-old infants were tested in the one-box condition described above. Unlike the $4\frac{1}{2}$-month-old infants, these older infants looked reliably longer at the impossible than at the possible event, suggesting that they (1) represented the height and location of the occluded box; (2) used this information to estimate at what point the screen would reach the occluded box; and therefore (3) were surprised by the impossible event in which the screen continued rotating past this point. A control condition carried out without the box supported this interpretation.

Together the results of the experiments just described suggest that at $4\frac{1}{2}$ months of age, infants realize that, when a box is placed in the path of a rotating screen, the box's height and location affect at what point the screen will stop. However, infants can reason only qualitatively about the screen's stopping point: They succeed at detecting violations only when they are able to compare visually the height of the screen to that of a second, identical box (e.g., "The screen is aligned with the top of the box"). When forced to reason about the absolute height and location of the box behind the screen, infants fail to detect even extreme violations (for further evidence of qualitative reasoning about arrested-motion phenomena in 4-month-old infants, see Spelke et al., 1992). By $6\frac{1}{2}$ months of age, however,

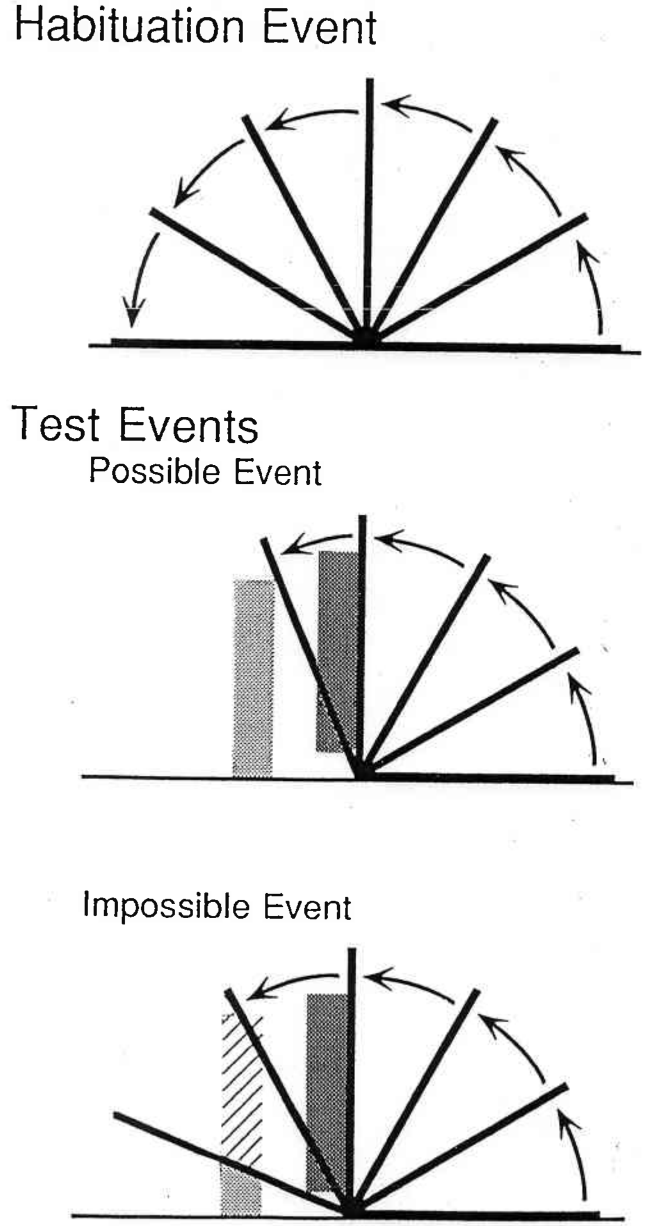

FIGURE 11.18 Test events used in Baillargeon (1991, experiment 4). Side view.

infants have progressed beyond this point; they can use their representation of the box's height and location to estimate at what point the screen will stop.

Discussion How should the developmental sequences described in this section be explained? These sequences are unlikely to reflect the gradual maturation of infants' quantitative reasoning or information-processing abilities, because the same pattern recurs at different ages for different physical phenomena. To what other phenomenon-specific changes should the sequences be attributed? One possibility is that, when first reasoning about a continuous variable, infants have difficulty encoding or retaining quantitative information about the variable.

Some evidence for this explanation comes from an experiment that examined $12\frac{1}{2}$-month-old infants' ability to encode and remember the size of a protuberance in a cloth cover (Baillargeon and DeVos, 1994b). At the start of each test event, the infants saw a cover with a small protuberance (figure 11.19); this cover was identical to that used in our previous unveiling experiments (Baillargeon and DeVos, 1994a, 1994b). Next, the cover was hidden by a screen. A gloved hand then reached behind the screen, retrieved the cover *with* its protuberance, and deposited it on the apparatus floor. In the possible event, the cover was identical to that shown at the start of the event. In the impossible event, the cover was more than twice as large as the initial cover. The infants tended to look equally at the two events, suggesting that they had not encoded or could not remember the size of the cover shown at the beginning of each event.

This negative result sheds light on the failure of the $12\frac{1}{2}$-month-old infants in the one-cover experiment to show surprise at the large toy dog's retrieval (Baillargeon and DeVos, 1994b) (see figure 11.14). Clearly, if the infants did not know the size of the hidden cover, they could not judge which size dog could have been hidden under the cover. From this perspective, the finding that $12\frac{1}{2}$-month-old infants were also unsuccessful when a second cover was placed to the left of the screen (Baillargeon and DeVos, 1994b) (see figure 11.13) suggests that they either could not encode infor-

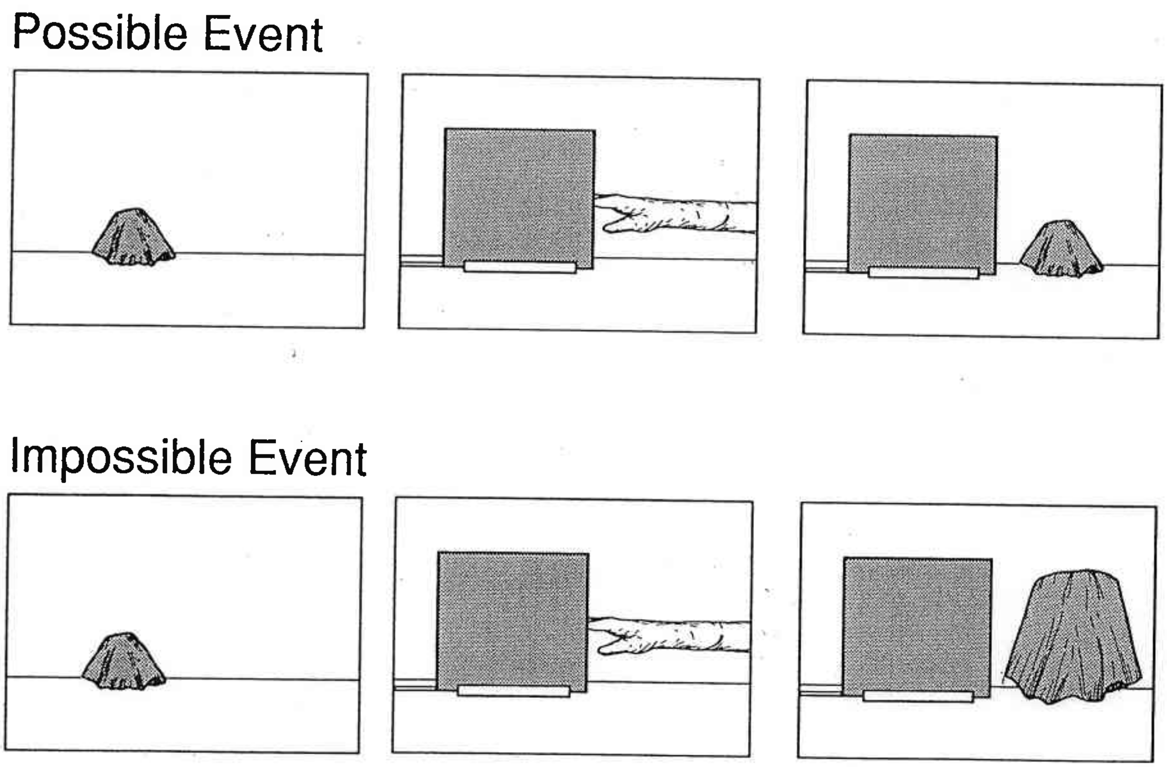

Figure 11.19 Test events used in Baillargeon and DeVos (1994b, experiment 4).

mation about the absolute size of the second cover or could encode this information but could not retain it even for the very brief interval required to shift their gaze from the cover to the dog and compare their representation of each item.

Other explanations could be advanced for the developmental sequences described in this section. For example, it could be that infants *are* able to encode and retain quantitative information about newly identified continuous variables but that these initial quantitative representations are so imprecise that they do not allow infants to detect even the marked violations shown in the present experiments. Further research is needed to evaluate this and other related explanations.

Concluding remarks

The model described in this chapter suggests that in learning to reason about a novel physical phenomenon, infants first form an all-or-none concept and then add to this initial concept discrete and continuous variables that are discovered to affect the phenomenon. Furthermore, after identifying continuous variables, infants succeed in reasoning first qualitatively and only later quantitatively about the variables.

This sketchy description may suggest a rather static view of development in which accomplishments, once attained, are retained in their initial forms. Nothing could be farther from the truth, however. Our data suggest that the variables infants identify, like the qualitative and quantitative strategies they devise, all evolve over time. To illustrate, when judging whether a box resting on a platform is stable, infants initially focus exclusively on the amount of contact between the box's bottom surface and the platform and, as a consequence, treat symmetrical and asymmetrical boxes alike. By the end of the first year, however, infants appear to have revised their definition of this variable to take into account the shape (or weight distribution) of the box (e.g., Baillargeon, in press, a). Similarly, evidence obtained with the rotating screen paradigm suggests that infants' quantitative reasoning continues to improve over time (e.g., $6\frac{1}{2}$-month-old infants can detect 80% but not 50% violations, whereas $8\frac{1}{2}$-month-old infants can detect both), as does their qualitative reasoning (e.g., $6\frac{1}{2}$-month-old infants will make use of a second box to detect a violation even if this second box differs markedly in color from the box behind the screen, whereas $4\frac{1}{2}$-month-old infants will not) (Baillargeon, 1993, in press, a).

The model of the development of infants' physical reasoning proposed here leaves many questions unanswered. In particular, what are the innate constraints that guide infants' identification of initial concepts and variables? Are these constraints purely formal, as we suggested earlier, or will it be necessary, to explain learning, to include substantive information about the nature or properties of objects? Furthermore, what consitutes a physical phenomenon? Should all events that reflect the operation of a same principle (e.g., impenetrability or gravity) be viewed as instances of the same phenomenon, or should phenomena be defined more narrowly, as in the preceding examples, in terms of specific types of interactions between objects?

In an attempt to shed light on these and related questions, we have opted for a dual research strategy. The first is to examine the development of infants' understanding of additional physical phenomena (e.g., arrested-motion, occlusion, and containment phenomena) to determine how easily these developments can be captured in terms of the patterns described in the model. With respect to arrested-motion phenomena, for example, one could ask whether infants younger than $4\frac{1}{2}$ months of age realize that a rotating screen should stop when a box stands in its path but are not yet aware that the height and location of the occluded box can be used to predict at what point the screen will stop. Our second strategy, which was alluded to earlier, is to attempt to teach infants initial concepts and variables to uncover what kinds of observations and how many observations infants require for learning. Would infants younger than $6\frac{1}{2}$ months of age, for example, be able to abstract the variable "amount of contact" in reasoning about support if provided with a set of pertinent visual obversations? We hope that the pursuit of these two strategies eventually will allow us to specify the nature of the mechanisms that infants bring to the task of learning about the physical world.

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NOTES

1. Spelke and her colleagues have also investigated young infants' intuitions about support relations between objects (e.g., Spelke et al., 1992, 1994a, b). Their results, however, have tended to be negative. See Baillargeon, Kotovsky, and Needham (in press) for a description of these results and possible explanations of the discrepancy between these and the present results.
2. To render the test events shown to the infants in the experimental and the control conditions more comparable, the right wall of the apparatus was also moved in the experimental test events. In each event, the wall was positioned 10 cm from the front end of the bug. In addition, the infants saw the two wall positions on alternate habituation trials (see figure 11.6). Analysis of the habituation data revealed that the infants showed no reliable preference for either wall position.
3. The small, medium, and large cylinders were made of identical material, so their sizes and weights could be expected to covary. Because our data are insufficient to determine whether infants based their predictions on the cylinders' sizes or weights, we will refer only to the sizes of the cylinders.
4. We have discussed at length how infants encode information about the size of the cylinder; but what about the distance traveled by the bug in each event? It seems likely that infants encode this information not in quantitative terms (e.g., "The bug traveled *x* as opposed to *y* distance") but rather in qualitative terms, using as their point of reference the track itself (e.g., "The bug rolled to the middle or the end of the track"), their own spatial position (e.g., "The bug stopped in front of me or rolled past me"), or the brightly decorated back wall of the apparatus (e.g., "The bug stopped in front of this or that section of the back wall").

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